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Exploring Rooftop Rainwater Harvesting Potential for Food Production in Urban Areas

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Abstract: Homegrown fruits and vegetables are gaining popularity in many metropolitan areas with several facets connected to the wider urban agriculture phenomenon. At the same time, the relationship between urban food production and irrigation water is pivotal in terms of resource management. In this paper, we investigated water savings through the collection and use of harvestable rainwater from buildings' rooftops to irrigate 2631 fruits and vegetables gardens in the urban area of Rome (Italy). The methodology makes use of existing geospatial data and data derived from satellite image classification to estimate food gardens' irrigation requirements and harvestable rainwater from nearby buildings' rooftops. The comparison of the annual harvestable rainwater with irrigation needs allowed for computing the proportion of water self-sufficient gardens as well as the amount of gardens whose water needs might be partially fulfilled with rainwater. Statistics were produced by land use type (horticulture, mixed crops, olive groves, orchards, and vineyards) and under the hypothesis that irrigation systems with low and high field application efficiency might be employed. We found that 19% and 33% of the gardens could be water self-sufficient for the low and high irrigation efficiency scenario, respectively. The remaining gardens, by using the available rainwater, could satisfy 22% (low efficiency) and 44% (high efficiency) of the water needs resulting in a reduction in the use of conventional water sources.

Keywords: rooftop rainwater harvesting; urban agriculture; irrigation water requirement; food garden; urban water management; object-oriented classification

1. Introduction

Local food production, food sustainability, environmental stewardship, and community resilience provided by urban agriculture (UA) in the Global North are increasingly gaining relevance [1–3]. The literature recognises that edible vegetable production is intertwined with other concepts such as food security and nutrition [4–6], ideas of beautification [7], social interactions and education [8], and leisure and exercise [9]. As recently stated by Sanyé-Mengual et al. [10], UA has essentially two primary social roles; at the community level, to guarantee and integrate fresh food for low-income communities while, at the individual level, the motivations are embedded into a more general framework that encompasses urban self-sufficiency, well-being, self-fulfilment, life style, and urban sustainability [1,11,12]. There is a growing body of cross-sectional studies emphasizing the importance of farming practices across urban areas, strongly linked to the development of circular economy actions and flow synergies of products and services towards a more sustainable quality of life [1,13]. In this sense, recent projects such as Fertilecity [14], Roof Water-Farm [15] and FOODMETRES [16] recognise the key role played by UA on these topics. Furthermore, in cities, as a key component of the urban green infrastructure system [17,18], UA and food production can contribute to sustain ecosystem services such as biodiversity and habitat for species [19,20], promote cultural services [21], improve waste recycling [22], soil quality [23], and stormwater retention [24].

The critical role played by the increasing demand of water resources in the world's large cities with strong population growth is acknowledged by existing research and at different policy levels [25]. This applies particularly in the domain of the food supply and distribution system [26] in the context of the water-food-energy-ecosystems nexus [27]. In a globalizing world, water resource sustainability [28] should be managed in a framework of scarce resources and competition among different urban water uses (e.g., UA, landscape irrigation, households) where new and smart solutions need to be explored to tackle the emerging challenges in urban hydrology [29]. The issue is more relevant in Mediterranean climates, especially in the dry season, where trade-offs related to water use increase with the combination of a high evapotranspiration and low rainfall [30] and sometimes require imposing water conservation and watering restriction programs [31]. Additional concerns may arise in relation to future climate changes and their consequent impact on the water budget, if we consider that irrigation for food production in cities is often carried out with tap water, therefore adaptation strategies through improved water management will be mandatory [32]. The growing role of UA [33] calls for sustainable irrigation management by adopting techniques and measures for water saving and water availability with more robust urban water infrastructure to counterbalance water stress and scarcity. Alternative irrigation sources such as rainwater harvesting systems (RWHs), a technique of the collection and storage of rainwater into natural reservoirs or tanks, can efficiently contribute to the development of more sustainable UA activities by reducing the use of other irrigation sources [34]. RWHs represent a reliable alternative in areas with water shortages (i.e., Mediterranean areas, arid and semi-arid climates) ensuring environmental and economic benefits over traditional water supply methods [35].

Geospatial and climate data integration coupled with the assessment of crop water requirements and the availability of rainwater at the urban level can play a pivotal role in fostering sustainable promotion and planning of urban cultivated areas. The last decade has seen the diffusion of Digital Earth tools and geodatasets (e.g., Google Earth, Google Maps, Microsoft Bing Maps, etc.), allowing us to explore the urban environment through updated remotely sensed images with spatial resolutions suitable for collecting detailed information on cultivated areas [36] and for characterizing urban features [37,38]. Geospatial techniques have been applied to explore potential scenarios of food self-reliance [39] and of food production integration in city spaces such as rooftops, green areas, and vacant lands [20,40–42] in developed and developing countries. Geomatics techniques such as object-oriented classification of very high resolution (VHR) images applied in UA, provide an exciting opportunity to advance our knowledge for the optimal design of RWHs for irrigation based mainly on rooftops in urban areas [34,43–45].

The aim of this study is to investigate the rainwater harvesting potential and irrigation water requirement of residential gardens (RGs) located in the urban area of the city of Rome, Italy. In detail, we focus on the following research questions:

- How much water is necessary to irrigate the crops in RGs located within the urban area of Rome?
- What is the total amount of harvestable rainwater from buildings' rooftops located nearby each RG?
- What is the share of irrigation water demand of RGs that can be satisfied through the collectable rainwater from rooftops?

Also, we raise the issue of urban water management where urban food cultivation is a competitor for the other water users, suggesting that awareness and future research questions are more than ever relevant to urban farmers and city planners. This is the time when the growth and enthusiasm around UA have to be coupled with science-based and technically sound advances to fill the knowledge gaps on the food production in urban ecosystems, a critical point to ensure the economic and environmental sustainability of UA [46].

2. Materials and Methods

2.1. Study Area

This study takes into consideration RGs devoted to food production located in Rome (Italy) within the Grande Raccordo Anulare (GRA), the highway ring delimiting a surface area of 344 km^2 and 68 km in circumference (Figure 1).

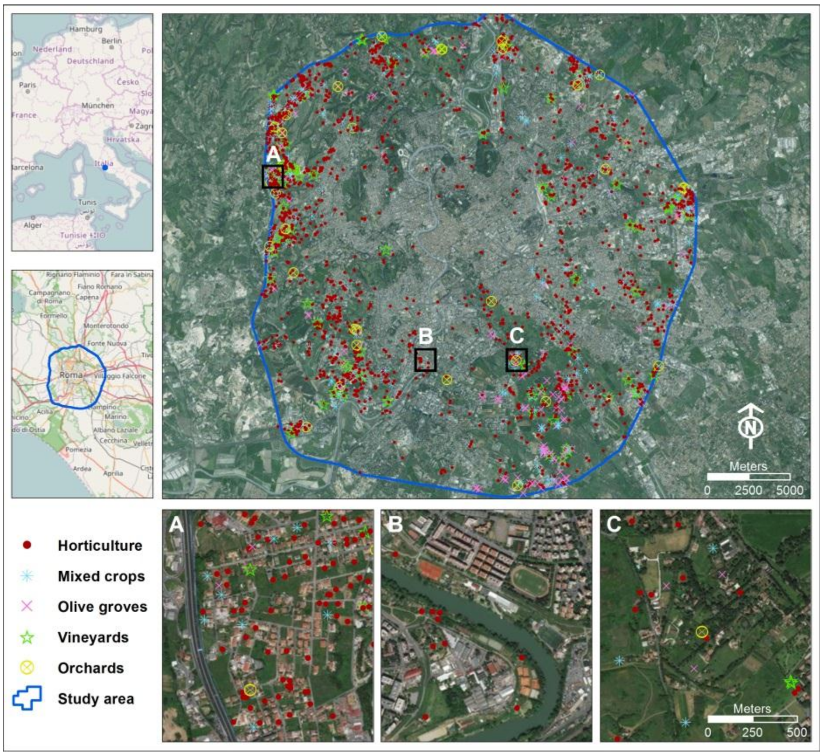


Figure 1. The urban area of Rome delimited by the highway ring (in blue) called Grande Raccordo Anulare (GRA). Residential gardens (RGs) polygons are depicted by their centroid and classified into five agricultural land uses: horticulture, mixed crops, vineyards, orchards, and olive groves. Examples of spatial arrangements of RGs in different urban settings are depicted in boxes A, B, and C.

Rome has an administrative area of about 1280 km^2 with 2.86 million inhabitants [47], and the topography ranges between 0 and 377 m above sea level. Climatic characteristics follow the Mediterranean pattern, with mild and moist winters and hot summers. A recent study [48] based on thermo-pluviometric data from 40 meteorological stations for the period from 1984–2014 revealed an average precipitation of 793 mm/year in the urban area with a trend of increasing precipitation in winter followed by a strong decrement in spring and stability in summer. As far as temperatures are concerned, isotherms define a decreasing trend linked to the topography while high values are clearly found in the city centre, due to anthropogenic impacts [48].

Since the early 1960s, urbanization and population have grown, causing an intense urban sprawl. Given the large extension of the municipal area, the urban dynamics saved large patches of green and vacant lands within the GRA acting as a fertile substrate where UA initiatives have been developed (e.g., urban farms, community gardens, etc.).

Today, crop production occurs in residential areas as well, with numerous sites located outside consolidated cities, where the settlements' structure is made by small and medium sized plots of nearby buildings. RGs constitute the most relevant UA typology carried out by citizens for self-consumption with a steady expansion registered during the period from 2007–2013 when cultivated plots increased from 2399 to 2717, extending for more than 102 ha and accounting for more than three-quarters of the UA sites detected within the study area [49].

2.2. Datasets

2.2.1. Climatic Data

Climatic variables, namely precipitation and evapotranspiration, are the key elements for modelling and estimating crop irrigation water requirements. Precise modelling usually requires data with high temporal (e.g., daily values) and spatial resolution (or at least compatible with the scale of the application). In addition, to perform spatially-explicit evaluations, climatic variables are regionalized by creating climatic surfaces where the spatial resolution and accuracy depend on availability, spatial distribution, and density of the meteorological stations in the study area.

Since long time series of meteorological data were not available for the study area, the WorldClim layers were selected [50]. WorldClim provides global climate layers in a raster format up to a spatial resolution of 30 arc-seconds (approximately 1 km^2). The spatialized climatic variables are generated by the interpolation of average monthly climate data from weather stations. Data are available for different conditions: "current" (interpolation of observations from weather stations for the 1960–1990 reference period and 1950–2000 for some areas), "future" (downscaled data from global climate models), and "past" (downscaled paleoclimate data from global climate models). A comprehensive description of the datasets, variables, and methods used to generate the climate layers can be found in Hijmans et al. [51].

Global coverage, open access, and straightforward data manipulation enables routine mapping applications and spatial modelling within Geographic Information System (GIS) as raster grids. WorldClim has been extensively used for several studies such as the analysis of the impact of climate change on agriculture and adaptation strategies by using crop–climate simulation models [43,52], as well as spatially explicit and physically based global models for water balance [53].

First of all, grids were downloaded from the WorldClim data portal, namely monthly precipitation (P, mm), mean (T_{mean}, °C), and maximum (T_{max}, °C) and minimum temperature (T_{min}, °C) as tiles covering the study area for the "current" conditions. Given the size of the study area, the available grids' resolution (1 km^2) was deemed satisfactory to ensure an acceptable level of climatic spatial variability for the subsequent characterization of the RGs. Twelve raster files, one for each month, were extracted for every climatic variable relative to the average values throughout the period from 1950–2000.

After collection, grids were pre-processed with the software QGIS [54]. Geospatial functions were employed to perform coordinate system conversion and projection (UTM, WGS84, Zone 32 N), and to assign monthly averages of the climatic variables to every single RG polygon located inside the corresponding 1 km^2 grid cell.

After pre-processing the grids, the monthly reference evapotranspiration (ET_o, mm) was computed through QGIS raster functions by applying the so-called 1985 Hargreaves equation [55], the most straightforward and suitable formulation applicable with the available climatic parameters:

$$ET_o = 0.0023 \cdot RA \cdot (T_{mean} + 17.8) \cdot (T_{\max} - T_{\min})^{0.5} \quad (1)$$

where T_{mean}, T_{max}, and T_{min} are the monthly average temperature grids from WorldClim in °C for the period from 1950–2000, 0.0023 is an empirical coefficient, and RA is the extra-terrestrial radiation on top of the atmosphere (mm/month as equivalent of evaporation) computed according to the methods reported in Allen et al. [56].

2.2.2. Residential Garden Geodatabase

The spatial dataset of the RGs devoted to food production was obtained from the urban agriculture spatial inventory created by Pulighe and Lupia [49]. The mentioned inventory is the first one created for the urban area in Rome through photointerpretation by using the very high resolution imagery provided by different webmapping tools (i.e., Google Earth, Microsoft Bing Maps, Google Maps, and Google Street View) and by integrating ancillary data. The detailed geodatabase documents the cultivated polygons identified inside the GRA area and are classified in different classes according to specific characteristics (i.e., community gardens, residential gardens, illegal gardens, institutional gardens, and urban farms). The agricultural land use is also associated to each polygon according to the following classes: orchards, mixed crops, olive groves, horticulture, and vineyards.

Our dataset of RGs was extracted from the original geodatabase (2717 cultivated polygons) by setting a restriction on the area size in order to consider only polygons smaller than 2000 m^2. A visual check of the dataset confirmed that parcels are generally linkable to a main residential building being located in the front yard or back yard, or at least nearby areas. The 86 polygons larger than 2000 m^2 were excluded since they were considered as parcels not strictly connected with residential buildings and located at far distances. By observing Figure 1, it is quite clear how the spatial distribution of RGs shows a strong densification at a certain distance from the city centre, where larger unsealed spaces are available. Conversely, in the city centre the artificial areas are dominant and RGs are rare or too small to be detected by the mapping methodology. In general, small to medium sized parcels are located nearby buildings in residential areas, while the larger parcels are mainly located outside the densely built-up areas.

The RGs dataset contains 2631 polygons with a total cultivated area of about 720,000 m^2 (72 ha). Table 1 shows the main statistical characteristics in terms of area, number, and percentage of patches classified into the five agricultural land use classes.

As far as it concerns the land use, RGs are dedicated mainly to horticulture (85.4% of the plots and 66.9% of the total dataset area), followed by mixed crops, olive groves, vineyards, and orchards; this pattern is observed both in terms of farmed area and number of plots.

Table 1. Descriptive statistics of residential gardens (RGs) by agricultural land use and for the whole RGs dataset.

Land Use	Plots		Area (m^2)					
	N	%	Min	Max	Mean	SD [1]	Total	%
Horticulture	2246	85.4	6.0	1970.5	214.2	261.1	481,024.6	66.9
Mixed crops	178	6.8	37.3	1970.1	527.2	450.3	93,835.6	13.0
Vineyards	79	3.0	44.3	1659.4	482.5	389.3	38,118.3	5.3
Orchards	36	1.4	100.9	1426.4	540.9	350.2	19,473.1	2.7
Olive groves	92	3.5	104.4	1983.2	945.2	513.2	86,959.6	12.1
RGs dataset	**2631**	**100.0%**	**6.0**	**1983.2**	**273.4**	**335.4**	**719,411.1**	**100.0**

[1] Standard deviation.

2.2.3. Buildings' Rooftop Geodatabase

Rooftops in the study area were extracted from satellite image processing. A geodatabase was obtained from a series of VHR WorldView-2 satellite images (geometric resolution $\leq$ 1 m) acquired in 2012, whose characteristics are reported in Table 2.

Table 2. Characteristics of the very high resolution (VHR) WorldView-2 satellite images.

Parameter	Image Name			
	01_P02	**_01_P03**	**_01_P01**	**_01_P04**
Image descriptor	ORStandard2A	ORStandard2A	ORStandard2A	ORStandard2A
Date (YYYY-MM-DD)	2012–08–20	2012–08–20	2012–10–19	2012–05–04
Mean azimuth (Degree)	249.3	271.2	162.8	157.1
Mean off-Nadir view angle (Degree)	18.1	16.4	3.9	10.8
Time (UTC)	10:43:27	10:43:12	10:30:26	10:23:02
Mean Ground Sample Distance (m)	0.522	0.503	0.466	0.484

Four pansharpened images were orthorectified using 54 Global Positioning System/Global Navigation Satellite System with Real-time Kinematic correction (GPS/GNSS RTK) control points, equally distributed on the frame, and a digital elevation model obtained from Light Detection And Ranging (LiDAR) data. A nearest neighbour interpolation was used to resample the images in the orthorectification process to guarantee the most conservative result in terms of radiometric information.

After the pre-processing, features were extracted from the images through an object-oriented classification approach [57,58] implemented in the eCognition Developer 9.1 environment [59]. The object-oriented method is based on two steps: image segmentation that defines image objects, and classification, which is based on a set of rules combining classification criteria based on the spectral signatures, shape of objects, and contextual relationships among objects.

The algorithm uses a bottom-up, region-growing technique, starting with one-pixel objects. From an arbitrary point in the original image, and in a number of iterative elaborations, the pixel objects are widened to larger pixel groups (segments) bearing a certain level of texture homogeneity. The segments are optimized using three homogeneity criteria: scale, shape, and colour. In this work, the segmentation results were tested with different scale values considering the target object dimension that corresponds to the building's rooftop mean size determined by sampling inside different subsets of the study area. The output of the segmentation process, the extraction of the rooftop polygons, and the relationships between the RG and the building's rooftops are depicted in Figure 2.

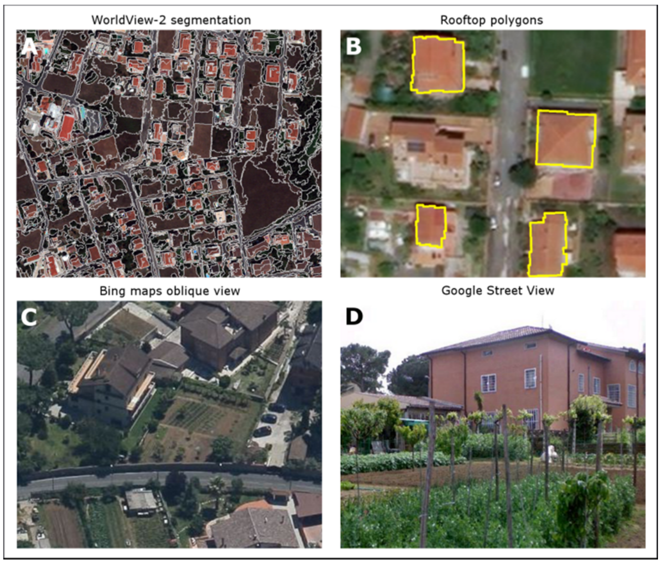


Figure 2. Output of the segmentation process (**A**). Extracted polygons from the segmentation layer representing the building's rooftop (**B**). Spatial relationship between RGs and rooftops depicted through a panoramic view from Microsoft Bing Maps (**C**) and field view captured with Google Street View (**D**).

The output produced a polygon vector layer representing the extracted buildings, later on imported and managed within QGIS. Each building polygon was considered coincident with the relative rooftop. The rooftop area was computed in m^2 and the polygon was associated to the nearest RG by considering the smallest Euclidean distance between its centroid and the RG through GIS spatial join operations. The spatial link between each RG and the corresponding rooftop was carried out without considering the ownership of the roof and of the RG by allowing a possible ownership inconsistency between the two polygons that might occur in the dataset. This issue was not addressed since property data were not available; however, no impact was expected neither on the irrigation water demand estimates nor on the rainwater harvesting computation.

2.3. Calculations

2.3.1. Irrigation Water Requirements

The irrigation needs of each RG was estimated by computing the Irrigation Water Requirement (IWR) over the classical Mediterranean irrigation season (April–September) with crops in dry conditions during the autumn and winter seasons. IWR for the irrigation season is the accumulated water (m^3), net of effective precipitation, needed to fulfil evapotranspiration for maximum plant growth and yield of a given crop in a specific climate regime:

$$IWR = \sum_{i=4}^{9} \left(k_c \cdot ET_{o(i)} - P_{eff(i)}\right) \tag{2}$$

where k_c is the mean crop coefficient (dimensionless) defined according to the land use of each parcel, and $ET_{o(i)}$ and $P_{eff(i)}$ are the reference evapotranspiration (m) and the effective rainfall (m) of the i-th month, respectively. The product k_c by ET_o is the crop water requirement under standard conditions [56]. Equation (2) simplifies the modelling of crop water requirement estimation by neglecting the effect of soil characteristics as well as the daily soil-plant-atmosphere water balance and the irrigation scheduling required to replenish the water lost by evapotranspiration.

Crop coefficients were considered as the mean of the values referred to by the three crop development stages (initial, mid-season, and late season) and assigned to each RG according to the corresponding land use (Table 3).

Table 3. Mean values of the crop coefficient (k_c) attributed to each agricultural land use.

Land Use	Crop Coefficient (k_c)
Horticulture	0.75
Mixed crops	0.66
Vineyards	0.48
Orchards and Olive groves	0.7

Values were derived from the database described in [60] where representative crop coefficients for Central Italy are gathered from different sources and used to compute the official statistics on irrigation at the farm level in the framework of the Italian Agricultural Census 2010. Mixed crops were considered as a combination of crops belonging to the other land uses, therefore the assigned crop coefficient was computed by averaging the coefficients of horticulture, vineyards, orchards, and olive groves. The parameter P_{eff} (i.e., net of foliage interception) can be calculated for each month as [61]:

$$\left\{ \begin{array}{ll} P_{eff} = 0.8P - 25 & if\ P > 75 \\ P_{eff} = 0.6P - 10 & if\ P < 75 \end{array} \right\} \tag{3}$$

where P is the precipitation in m.

In order to improve the water requirement estimation, the concept of field application efficiency [62], related exclusively to the irrigation system used, was taken into account by calculating the Gross Irrigation Water Requirement (GIWR), in m^3:

$$GIWR = \frac{1}{E} \cdot IWR \tag{4}$$

where E is the field application efficiency of the irrigation system (dimensionless) and IWR is the value computed with Equation (2). We computed the values of GIWR for each RG under the hypothesis that two irrigation systems with extremely different field application efficiencies are used: surface (e.g., border, furrow, and basin) and localized (i.e., drip irrigation). The values of 45% and 90% were assigned to the surface and localized irrigation systems, respectively.

2.3.2. Rooftop Rainwater Harvesting

The amount of rainwater potentially intercepted and collected by every rooftop was estimated by considering the rooftop size and the monthly average precipitation values for the period from 1950–2000 available as 1 km^2 gridded data. The potential amount of collectable rainwater was computed by the equation:

$$RH = P_{tot} \cdot A_{roof} \cdot C \quad (5)$$

where RH is the yearly amount of harvestable rainwater from the building's rooftops (m^3), P_{tot} is the total annual precipitation (m), A_{roof} is the rooftop area (m^2), and C is the harvesting efficiency of the system (dimensionless), often indicated as the runoff coefficient. We considered a conservative value of efficiency of 60% for the catchment area to compensate for the effects of leaks, wind, and rainfall rates. In this sense, the literature reports values between 70% and 95% resulting from the interaction of climatic and architectural factors [63]. High efficiency values (up to 95%) can be reached if the system is in perfect condition (no leaks) and during a period with slow gentle rain. Conversely, during fast and heavy rain events, the efficiency will be lower (60–75%) since gutters overflow and gutter covers are overrun with water.

Generally, rooftop RWHs store the accumulated water in tanks to be used for different household purposes. We made a simplification by neglecting the design and modelling of the system (i.e., tank sizing and tank water balance), the cost-benefit analysis, and any consideration about the space requested for installing the tank for each RG. Therefore, the results are produced by assuming that the whole amount of rainwater collectable annually is used to irrigate RGs in the period from April–September without considering the water budget of the tank (i.e., the balance among irrigation requests, rainwater stored, and tank overflow).

3. Results and Discussions

The combination of the parameters related to climate, agricultural land use, and crop characteristics allowed us to estimate, for the irrigation season (April–September), the cumulated Gross Irrigation Water Requirement (GIWR). GIWR was adjusted for field application efficiency by considering two extreme scenarios: surface irrigation—low efficiency (GIWR45) and drip irrigation—high efficiency (GIWR90). The statistical summary is reported in Table 4 for each agricultural land use and for the RGs dataset as a whole.

Table 4. Descriptive statistics by agricultural land use for Gross Irrigation Water Requirement (GIWR) cumulated over the irrigation season computed for two irrigation systems with efficiencies of 45% (GIWR45) and 90% (GIWR90).

Land Use	GIWR45 (m^3)					GIWR90 (m^3)				
	Min	Max	Mean	SD [1]	Total	Min	Max	Mean	SD [1]	Total
Horticulture	7	2265	246	300	552,186	3	1133	123	150	276,093
Mixed crops	43	2337	609	526	108,349	22	1168	304	263	54,174
Vineyards	51	1950	557	454	43,998	26	975	278	227	21,999
Orchards	114	1671	622	406	22,389	57	836	311	203	11,194
Olive groves	117	2333	1097	594	100,886	59	1166	548	297	50,443
RGs dataset	**7**	**2337**	**315**	**388**	**827,808**	**3**	**1168**	**157**	**194**	**413,904**

[1] Standard deviation.

The whole set of RGs requires a total amount of water of more than 800,000 m^3 for GIWR45, while the volume clearly drops by half when GIWR90 is considered. In terms of agricultural land use, the largest share of irrigation is required by horticulture, the category with the largest number of cultivated parcels. At the same time, horticulture has the smallest mean irrigation values among all categories being constituted mainly by small parcels.

The results provided by the object-oriented classification enabled us to compute the geometric features of the buildings' rooftops and the distances to the nearest RG. Table 5 reports the main statistical characteristics aggregated by agricultural land use.

Table 5. Descriptive statistics of the buildings' rooftop dataset by agricultural land use and for the whole RGs dataset.

Land Use	Roof Area (m^2)						RG-Roof Distance (m)			
	Min	Max	Mean	SD [1]	Total	%	Min	Max	Mean	SD [1]
Horticulture	2	2511	147.6	193.5	331,593	85.3	2.0	427.9	30.1	31.6
Mixed crops	7	1567	152.1	190.9	27,067	7.0	6.3	173.5	30.9	26.0
Vineyards	7	543	150.4	114.1	11,885	3.1	11.4	358.7	41.8	45.7
Orchards	11	208	92.4	55.5	3325	0.9	9.2	457.5	46.4	75.1
Olive groves	15	1566	162.3	209.3	14,936	3.8	10.6	469.3	64.3	65.1
RGs dataset	**2**	**2511**	**147.8**	**190.8**	**388,806**	**100.0**	**2.0**	**469.3**	**31.9**	**35.0**

[1] Standard deviation.

The whole set of rooftops constitute a surface for rainwater interception of more than 380,000 m^2 (38 ha). In terms of rooftop area, the widest range is found for horticulture (from 2 to more than 2500 m^2). This wide range is determined by the fact that the procedure extracted every possible building or artificial structure located nearby the RGs (from very small toolsheds, to pergolas, up to large buildings or warehouses). Rooftops associated to orchards have the smallest values of mean area, range, and dispersion around the mean. In terms of the RG-roof distance, values range from 2 to about 470 m, while the smallest mean distance occurs for horticulture and the largest one for olive groves. Statistical features of RH are summarised in Table 6 by agricultural land use.

Table 6. Descriptive statistics of the rainwater harvestable (RH) from buildings' rooftops linked to RGs by agricultural land use.

Land Use	RH (m^3)				
	Min	Max	Mean	SD [1]	Total
Horticulture	1	1189	70	92	156,398
Mixed crops	3	728	72	91	12,813
Vineyards	3	263	71	54	5606
Orchards	5	95	43	26	1564
Olive groves	7	745	77	100	7112
RGs dataset	**1**	**1189**	**70**	**91**	**183,493**

[1] Standard deviation.

The annual amount (January–December) of RH from the whole set of roofs associated to RGs exceeds 180,000 m^3. Mean values are around 70 m^3 for all land uses except for orchards that have smaller value (43 m^3). The widest range occurs for horticulture (from 1 to 1189 m^3) due to the large range of sizes of the linked roofs. When the total area covered by buildings' rooftops and the corresponding total harvestable rainwater is considered, each square meter of roof could potentially harvest 0.47 m^3 of water. The comparison between GIWR and RH allowed us to identify water self-sufficient parcels, namely the parcels where irrigation can be completely satisfied by the harvestable rainwater from the linked buildings' rooftops. We considered all the available intercepting surfaces neglecting the economic feasibility of the RWHs that could limit the implementation to only those RGs connected with a minimum rooftop size. Figure 3 reports the number of parcels (percentage over the total) that can achieve water self-sufficiency for the two scenarios for each agricultural land use and for the RGs dataset as a whole.

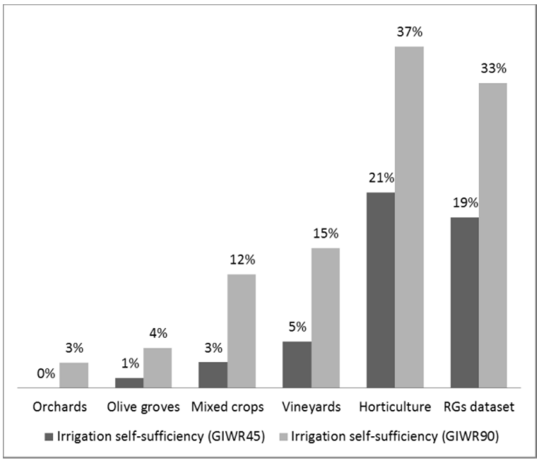
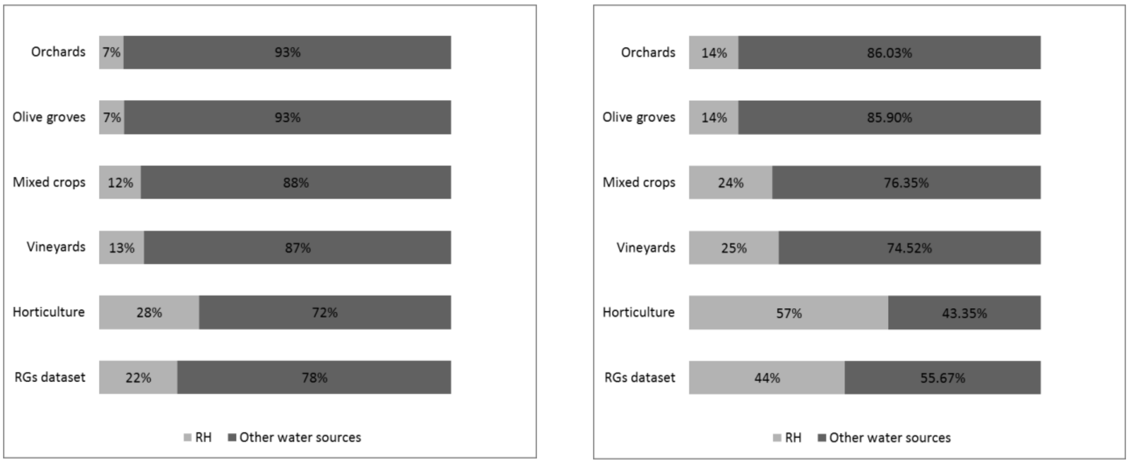


Figure 3. RGs (percentage over the total) that potentially can satisfy the irrigation requirements solely with the harvestable rainwater from nearby buildings' rooftops by agricultural land use and for the dataset as a whole. Two scenarios are considered: irrigation with low and high efficiency systems.

Interestingly, about one-third of the total (33% or 870 parcels) could satisfy irrigation with the harvestable rainwater if high irrigation efficiency was considered. Conversely, water self-sufficiency is achievable by about one-fifth of the total (19% or 487 parcels) when low irrigation efficiency systems were employed. When parcels with water self-sufficiency are counted at the land use level, horticulture, the dominant land use in the area, reveals the largest share (one-fifth and more than one-third for low and high irrigation efficiency, respectively). In contrast, the lowest share occurs for orchards, the least represented land use in the area, with 0 and 3% of the parcels for low and high irrigation efficiency, respectively. An implication of this is the possibility that, whenever irrigation requirements cannot be satisfied completely by the yearly collectable rainwater, the missing amount has to be withdrawn from other sources (e.g., water mains, wells, etc.). As a consequence, impacts on the urban water balance can be relevant during water shortage periods, causing potential conflicts among water uses (i.e., agriculture, industry, potable water, landscape irrigation).

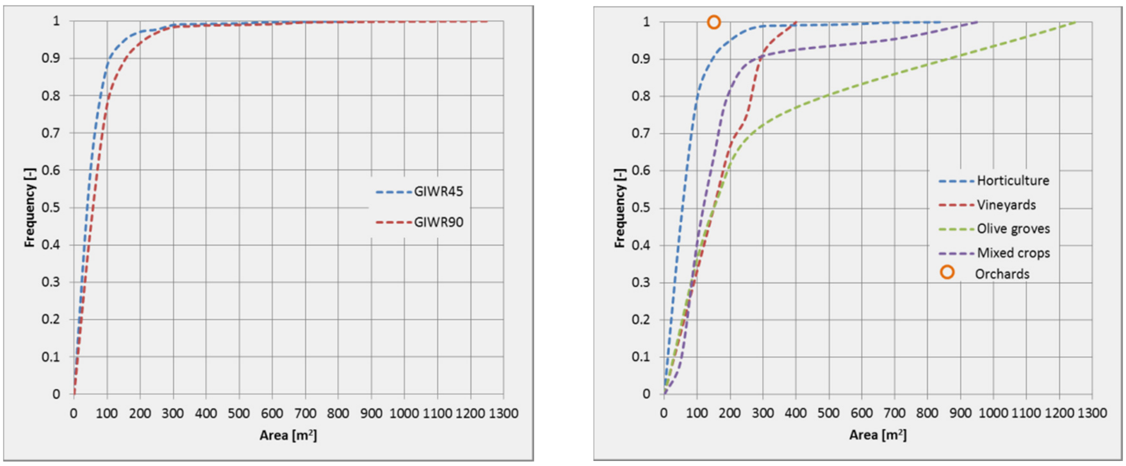
The subset of RGs that have to resort to other water sources is analysed in Figure 4 where the GIWR amounts provided either by RH or different sources are compared for the two irrigation efficiency scenarios (low, Figure 4a and high, Figure 4b) and by agricultural land use.

When high irrigation efficiency is considered for the whole subset, almost half (44%) of the GIWR can be met by RH, while the amount is curbed down to one-fifth (22%) in the case of a low irrigation efficiency system. Horticulture has the largest share of irrigation supplied by rainwater, either with the high or low irrigation system (57 and 28%, respectively). The frequency distribution of the size of the water self-sufficient parcels indicates that the maximum size of the parcels is 850 and 1250 m^2 for the GIWR45 and GIWR90 scenarios (Figure 5a). Interestingly, the majority (90%) of the parcels are smaller than 100 m^2 for GIWR45 and 150 m^2 for GIWR90. Therefore, given the crop types, rooftop size, and environmental characteristics considered, the collectable rainwater could mainly fully satisfy the irrigation requirements of small size parcels. The frequency distribution of water self-sufficiency RGs by agricultural land use for the two scenarios was also calculated (Figure 5b). The maximum size of the parcels varies by land use (olive groves: 1250 m^2; mixed crops: 950 m^2; horticulture: 850 m^2; vineyards: 400 m^2 and orchards: 165 m^2). In terms of number, the parcels vary by land use ranging from only one (orchards) up to 831 (horticulture). The majority (90%) of the water self-sufficiency parcels have the following sizes: 150 m^2 (horticulture), 165 m^2 (orchards), 300 m^2 (vineyards and mixed crops), and 830 m^2 (olive groves).



(**a**) (**b**)

Figure 4. Irrigation water requirements (percentage over the total) that can be met by resorting to collectable rainwater and other sources for the whole set of parcels belonging to different agricultural land uses. The dataset considered is the subset of RGs that cannot reach water self-sufficiency. Results are reported for the two scenarios: GIWR45 (**a**) and GIWR 90 (**b**).



(**a**) (**b**)

Figure 5. Frequency distribution of the water self-sufficiency RGs for the GIWR45 and GIWR90 scenarios (**a**). Frequency distribution of the water self-sufficiency RGs by agricultural land use for the GIWR90 scenario (**b**).

The aforementioned results show remarkable potential levels of water savings in the study area, expressed either as a percentage of water self-sufficiency RGs or as a percentage of RGs whose irrigation could be met partially by the harvestable rainwater. Results are in line with those obtained by Lupia and Pulighe [34] with a simplified approach, where roof size was set to 100 m^2 for all cultivated parcels (irrigation water savings between 5 and 35% depending on the land use when high irrigation efficiency is hypothesized). Smaller water savings (about 10%) were observed for home food gardens in Rome by modelling the tank water balance for toilet flushing (primary use) and irrigation (secondary use) [44]. Our findings suggest that collecting and storing rainwater from roofs can potentially provide an alternative irrigation source to be used by the RGs located in the urban area of Rome, reducing water costs and providing an additional resource during dry periods. In particular, the use of RH can reduce the usage of other sources (e.g., water mains, groundwater) with different intensities according to the type of irrigation system used and the agricultural land use. Interestingly, at the same time a portion of RGs can be considered water self-sufficient and no other irrigation source is needed. Furthermore, given the amount of harvestable rainwater in the study area, RH has the potential to minimize storm run-off and nutrient losses because vegetation holds water within the canopy and increases soil infiltration [64,65]. Insights from this study are applicable to other metropolitan areas when urban water use is addressed, especially in Mediterranean climates where municipal water use is higher than in northern climates due to different climate conditions and specific water uses [66]. Though a set of benefits are associated with RWHs, some barriers need to be considered. The reliability of the systems depend directly either on their characteristics or on the environment, making the water quantity variable in space and time [35]. Pollution, roof material, and environmental conditions may affect the quality of water collected with potential health risks for users that can be minimized with proper maintenance of the system [67]. Finally, political support (e.g., subsidies, regulations, etc.) and users' motivation (e.g., low when financial return occurs in the long-term) are required to drive the adoption of RWHs as a component of urban water management [68].

Our approach, though based on a simplification of the whole system and its components, casts light on potential water savings in urban areas where UA is becoming a new relevant water factor. Future studies on the current topic based either on more precise tank modelling or by including additional scenarios, is necessary for accurately defining strategies for urban water management. For instance, new scenarios based on the relationship between the growth of UA and the RWH systems would allow us to assess the sensitivity of the results obtained. Additional and more complete data would also be beneficial for the analysis. For example, meteorological data with greater spatial resolution would improve the estimation of irrigation requirements for each parcel during the irrigation season. Sophisticated modelling would be essential in case the results have to be used for urban planning strategies. In this view, several facets connected with RWHs and irrigation should be addressed, such as runoff water quality [63,69], tank water balance modelling, and performance [70–72] to define the suitable tank size by also taking into account other non-potable domestic water supply (e.g., WC flushing) and cost-efficiency analyses [68,73]. Guiding research efforts in this direction is of paramount importance, since water saving performance is highly affected by site-specific conditions such as the local rainfall pattern, the habits of the household dwellers, and the characteristics of the RWH and of the building [74].

UA is burgeoning and becoming relevant in both developing and developed countries, and therefore its impacts on urban resource management (water *in primis*) cannot be discounted anymore. Modelling water use in UA and identifying alternative water sources are pivotal components for resource-conscious urban planning and design, a context where both social and ecological process driving resource flows at different spatial and temporal scales have to be thoroughly understood [75]. In this context, resorting to geospatial information from different sources and image-based processing techniques (i.e., feature extraction by photointerpretation and semi-automatic imagery classification) are stepping stones for collecting information on land use/cover and resources at fine spatial resolution to investigate urban food production [49,76–78].

Furthermore, current and future climate scenarios call for approaches based on sustainable water use in all sectors, especially in Mediterranean climates, Southern Europe, and California. For instance, in Italy, water pressures arise from the agricultural sector (50% of the total water use) and from urban areas which account for more than 9 billion m^3 per year, with a daily consumption for each inhabitant greater than 0.25 m^3, one of the highest in Europe [79].

4. Conclusions

Extended knowledge on water use in urban environments has been gaining relevance during the last few years on many fronts as new methods, such as UA, are appearing. Urban water management and sustainable water use needs further attention, as potential conflicts may arise in countries (e.g., Southern Europe, California) where water shortages are frequent and expected to increase as a consequence of climate change.

This paper presents an approach for estimating irrigation water requirements and suggests a sustainable water use for RGs where vegetables and fruits are cultivated for self-consumption in the urban area of Rome (Italy). In particular, water self-sufficiency was explored for each cultivated parcel under the hypothesis that the building's rooftops located nearby might intercept rainwater to be stored and later used for irrigation. Irrigation water requirements and harvestable rainwater were estimated for a spatial dataset by taking advantage of the multi-source dataset created by different methodologies with adequate spatial resolution.

The extent to which RGs are irrigable with harvestable rainwater from rooftops is identified, along with an estimate of how many RGs could be water self-sufficient (i.e., irrigation water requirements are fully met by RH) for different land use types. The findings suggest that there is considerable water saving potential in the study area, where up to one-third of the RGs' water needs could be covered with the harvestable rainwater when high irrigation efficiency is considered.

The results provide a first assessment of one of the components of water use in urban areas when UA in residential areas is considered. This might contribute to raising awareness amongst local authorities and involve them in measures to provide information and advices to urban farmers.

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Abbreviations

GCP	Ground Control Point
GIWR	Gross Irrigation Water Requirement of a residential garden
GIWR45	Gross Irrigation Water Requirement of a residential garden corrected for an irrigation systems with the field application of 45%
GIWR90	Gross Irrigation Water Requirement of a residential garden corrected for an irrigation systems with the field application of 90%
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRA	Grande Raccordo Anulare
IWR	Irrigation Water Requirement of a residential garden
LiDAR	Light Detection And Ranging
RG	Residential Garden
RH	Rainwater Harvestable, the yearly amount of harvestable rainwater from the building's rooftops
RTK	Real-time Kinematic
RWH	Rainwater Harvesting System
SD	Standard Deviation
VHR	Very High Resolution
UA	Urban Agriculture

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